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Convergent Neural Networks in Meditation and Interoception: A Coordinate-Based Meta-Analysis of fMRI Studies

Master's Thesis

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Abstract

Meditation and interoception are closely related processes involved in attention, emotion regulation, self-awareness, and the perception of bodily states. Neuroimaging studies have suggested that both rely on overlapping brain regions, particularly the insular cortex and anterior cingulate cortex (ACC), yet their neural relationship has rarely been investigated directly. The present thesis aimed to examine the extent to which meditation and interoception share common neural mechanisms by conducting a coordinate-based meta-analysis of functional magnetic resonance imaging (fMRI) studies.

Activation Likelihood Estimation (ALE) meta-analyses were performed on studies investigating meditation and interoceptive processing, followed by conjunction and contrast analyses to identify shared and distinct patterns of brain activation. Results showed that meditation was consistently associated with activation in the ACC and medial frontal regions involved in attentional control and self-regulation. Interoception, in contrast, engaged a broader network including the bilateral insula, supplementary motor area, middle cingulate cortex (MCC), sensorimotor cortices, and parietal regions linked to bodily awareness and multisensory integration.

The analyses revealed convergence between the meditation and interoception literature within an insula–cingulate/medial frontal network, while no significant differences emerged between the two domains. The findings suggest that meditation and interoceptive processing rely on partially shared neural substrates and support the idea that meditation may function, at least in part, as a structured form of interoceptive attention.

Keywords: meditation, interoception, fMRI, Activation Likelihood Estimation (ALE), anterior cingulate cortex, insula, bodily awareness.

1. Introduction

In recent decades, cognitive neuroscience has increasingly examined meditation and interoception as processes involved in attention, emotion regulation, and self-related processing, along with their neural correlates, using techniques such as functional magnetic resonance imaging (fMRI) (Burke & Gonzalez, 2011; Fox et al., 2016). Meditation refers to a set of practices involving the systematic regulation of attention and awareness, associated with changes in cognitive control, emotional processing, and large-scale brain networks (Lutz et al., 2008). Interoception, in turn, refers to the perception and interpretation of internal bodily signals and plays a central role in homeostatic regulation, affect, and the construction of the self (Ceunen et al., 2016; Khalsa et al., 2018).

Importantly, both domains seem to share the involvement of key regions within broader large-scale networks, including the insula, anterior cingulate cortex (ACC), and prefrontal cortex (Berntson & Khalsa, 2021; Fox et al., 2016). Despite these parallels, they are rarely examined together, as most studies investigate meditation or interoception in isolation. Therefore, the extent to which meditation and interoception rely on common or distinct neural mechanisms remains unclear. Given the heterogeneity of individual fMRI findings, a systematic synthesis is needed to clarify their relationship and identify consistent activation patterns across both domains.

1.1. Meditation

Definition and Conceptualization of Meditation. The ancient practice of meditation has gained increasing attention in cognitive neuroscience due to its measurable effects on emotional and cognitive function.

The word “meditation” derives from the Sanskrit word *dhyana* which means attention or contemplation (Canter, 2003). The practice aims to cultivate self-awareness and psychological well-being through breathing techniques, the repetition of sounds and the focus of attention (Canter, 2003). It has been described as a skill involving mental and emotional control, nowadays common in both the East and West, used for therapeutic as well as religious or spiritual purposes (Thomas & Cohen, 2014).

Meditation has been difficult to define in a unified way due to the diversity of its forms. A scientific definition has therefore been necessary for empirical investigation. As Thomas and Cohen (2014) describe, meditation has been conceptualized as comprising three essential components: a defined technique, logic relaxation and a self-induced state/mode. Non-essential components of the definition include a state of psychophysical relaxation, the use of a self-focus skill or anchor, the involvement of an altered state of consciousness, to be embedded in a religious or spiritual context, and to involve an experience of mental silence (Thomas & Cohen, 2014).

Meditation has its origins in ancient India, where it was first described in the Vedic texts as an exercise aimed at accessing the deepest level of human consciousness (Sharma, 2015). Within this early framework, meditation was not used as a relaxation or coping technique, but rather as a means of reconnecting with the inner Self, in a state of pure awareness (Sharma, 2015). As the discipline of meditation spread through different cultural and philosophical settings, it morphed into numerous and diverse techniques such as contemplation, concentration, Yoga, breathing exercises, mantra, and many more. More recently, it has been adopted by Western contexts, where it is mostly practiced in psychological and medical frameworks, playing a significant role in contemporary Western conceptions of a healthy lifestyle (Sharma, 2015).

Clinical interest in mindfulness was sparked by the introduction of the Mindfulness-Based Stress Reduction (MBSR) program for chronic pain management by Jon Kabat-Zinn, which has since become a widely used intervention for reducing psychological morbidity (Bishop, 2004). More than five decades later, its psychophysiological benefits have been studied thoroughly, making it a preferred tool for modern models of psychotherapy, and contributing to the development of the third-wave of behavioural psychological techniques. Acceptance and Commitment Therapy (ACT), Dialectical Behavioural Therapy (DBT) and Compassion Focused Therapy (CFT) are some of the specific programs that incorporate mindfulness with the objective of reducing symptoms of stress, anxiety and depression, as well as enhancing emotional regulation and decreasing impulsive reactions (Christopoulou & Pavlopoulos, 2025). Apart from promoting health for patients, mindfulness also enhances the therapist's focus on the therapeutic process and strengthens the therapeutic alliance, therefore supporting positive treatment outcomes (Christopoulou & Pavlopoulos, 2025).

Cognitive and Affective Mechanisms. Two types of meditation are studied in the majority of research: mindfulness meditation and concentration meditation (Lutz et al., 2008).

Shapiro et al. (2018) describes mindfulness as "the awareness that arises through intentionally attending in an open, caring, and discerning way". It has been conceptualized as a multidimensional construct made up of two components: self-regulation of attention and orientation to experience (Bishop et al., 2004).

The first component, self-regulation of attention, implies bringing awareness to the current experience (such as thoughts, feeling and emotions), focusing on what is happening in the present moment. A key skill underlying this process is sustained

attention, defined as the ability to maintain a vigilant state over extended periods, thereby anchoring attention in the present moment and facilitating the detection of change. Another important skill involves *switching* from one object to another. The objective of mindfulness meditation is not to suppress thoughts, but rather to acknowledge them and then allow them to cease, switching once more back to the breath and preventing rumination (Bishop et al., 2004). By being released from elaborative thinking, attentive resources, which are limited in capacity, are made available for the current experiences. This results in what is often described as the "beginner's mind", the capacity of observing the present in an open-minded way, leaving behind our judgements, beliefs, expectations and assumptions.

As for the second component of mindfulness meditation, orientation to experience relates to an increased openness and curiosity for new experiences, even those painful or unpleasant (Bishop et al., 2004). This state is achieved through taking curious notice of the thoughts, feelings and sensations that arise in the body without trying to change them, therefore being accepting of one's current experience. In this way, emotional distress becomes more tolerable and thoughts and feelings are experienced as transient subjective events rather than an objective permanent reality (Bishop et al., 2004).

Instead, concentration (or focused attention) meditation involves focused attention on an intended object while disengaging attention from the source of distraction without further involvement, bringing it back to the intended object. Progress in this skill is evaluated by the amount of effort required to sustain the intended focus, with advanced levels of concentration being associated with a significant decrease in emotional reactivity (Lutz et al., 2008).

Subsequent research demonstrated that meditation is associated with increased activity in brain regions related to well-being, emotional regulation, and sustained attention (Sampaio et al., 2017).

Neuroimaging and Neural Mechanisms of Meditation. Scientific interest in meditation expanded considerably with the development of neuroimaging techniques capable of measuring brain activity and connectivity, including fMRI, electroencephalography (EEG), and magnetoencephalography (MEG) (Burke & Gonzalez, 2011). The application of these methods has shown that meditation is associated with changes in brain activity and, in some cases, structural brain organization (Sampaio et al., 2017). Importantly, these effects appear to emerge progressively with continued practice (Lutz et al., 2016; Trichal, 2026).

Consistent with this view, long-term meditation has been associated with stable reorganization of large-scale brain networks, with patterns that vary according to the specific meditation practice employed (Guidotti et al., 2021). Focused attention meditation has been associated with increased connectivity within attention-related networks, including the ACC and parietal regions. In contrast, open monitoring meditation has been linked to alterations in fronto-parietal and hippocampal networks involved in cognitive control and awareness, as well as reduced connectivity within regions of the default mode network (DMN), particularly the posterior cingulate cortex. These changes are thought to reflect reduced mind-wandering and self-referential processing (Guidotti et al., 2021). Therefore, different meditation practices appear to engage distinct brain networks that reflect their specific psychological goals, although some common regions are involved across techniques, including the insula,

pre/supplementary motor cortices, dorsal ACC, and frontopolar cortex (Fox et al., 2016).

Recent reviews further suggest that mindfulness meditation is associated with systematic modifications in large-scale functional brain networks (Trichal, 2026). In particular, mindfulness practice appears to influence the salience network, the default mode network, and the executive control network. Reorganization of these networks has been associated with enhanced emotional regulation, greater awareness of present-moment experiences, and reductions in perceived stress and pain (Trichal, 2026). By modifying neural systems involved in self-referential and emotional processing, mindfulness appears to promote psychological well-being and adaptive functioning (Trichal, 2026). Reduced activity in cortical midline structures associated with self-focused thinking may contribute to lower levels of rumination and anxiety, while increased awareness of ongoing emotional experiences may facilitate more effective emotional processing.

Attention-to-breath meditation training has been shown to strengthen connectivity between limbic and prefrontal brain regions involved in emotional regulation. In particular, improved stress and emotion regulation have been associated with stronger functional connectivity between the amygdala and the ventromedial prefrontal cortex (VMPFC) (Trichal, 2026). Mindfulness practitioners also exhibit increased frontal lobe activity, with greater activation of prefrontal regions linked to enhanced emotional awareness and fewer depressive symptoms. Furthermore, meditation appears to strengthen top-down regulatory processes by increasing dorsomedial prefrontal cortex (DMPFC) activity during cognitive emotion regulation tasks while reducing amygdala responses to negative emotional stimuli. Together, these findings indicate that

mindfulness enhances executive control over emotional processes, reduces limbic reactivity, and promotes more adaptive patterns of emotion regulation.

Effects of Meditation Training (short vs long term). Meditative practices can produce measurable cognitive effects in non-expert meditators after as little as eight weeks of training. Basso et al. (2019) found that a daily 13-minute guided meditation practice over an eight-week period led to reduced negative mood, improved attention, working and recognition memory, as well as decreased anxiety in non-expert meditators. In contrast, these effects were not observed after four weeks of practice, suggesting that a shorter duration of daily meditation may be insufficient to produce measurable changes in mood and cognitive functioning.

These findings support the notion that meditation represents a skill that develops progressively over time rather than a short-term intervention. Consistent with this perspective, Lutz et al. (2016) demonstrated that during meditation, experienced meditators exhibit greater reductions in cortical midline structures (e.g., medial prefrontal cortex and posterior cingulate cortex) associated with default mode network activity and self-referential processing, alongside reduced activation in left inferior prefrontal regions linked to verbalization and increased engagement of dorsal medial prefrontal/pre-supplementary motor area (SMA) regions involved in attentional control and monitoring, compared to novices. This suggests that such neural adaptations emerge through sustained and repeated training.

Compared with short-term training, long-term meditation is associated with more enduring neuroplastic changes, including structural increases in regions such as the prefrontal cortex, insula, and hippocampus, which are implicated in attention, interoceptive awareness, and emotional balance (Trichal, 2026). Experienced meditators

additionally show greater reorganization of large-scale networks, including the thalamic network and the default mode network (Trichal, 2026).

Over time, early functional changes in brain activity may become consolidated into more lasting structural adaptations, resulting in stronger and more persistent effects on cognitive and emotional functioning (Trichal, 2026). Taken together, findings across studies suggest that mindfulness develops along a continuum, whereby initial practice produces relatively rapid but less stable functional changes, while sustained practice over months or years consolidates these effects through structural and network-level reorganization. This process may underlie the lasting improvements in attention, interoceptive awareness, and emotion regulation observed in experienced meditators (Trichal, 2026).

Cognitive Outcomes. Evidence from neuroimaging studies suggest that meditation practice can have diverse cognitive and affective effects. The following section synthesizes key findings in these domains, ranging from improvements in attention, executive control, memory, self-referential processing, emotional regulation and stress reduction.

In line with this, evidence from meta-analyses indicate that mindfulness training is associated with small to moderate improvements in executive functioning and related cognitive control processes (Hadash et al., 2026). To better understand the neural mechanisms underlying these improvements, neurophysiological studies have examined the brain processes associated with executive control in meditators.

To begin with, Teper and Inzlicht (2013) examined the mechanisms through which mindfulness meditation enhances executive control. Their research indicates that improvements in executive control among meditators are implemented in the ACC, as

indexed by increased amplitude of the error-related negativity (ERN), a neural signal of error processing. These findings suggest that enhanced executive functioning may largely result from greater acceptance of emotional states in this population. Meditators are not only skilled in regulating emotions but are also efficient and effective in identifying them, as supported by the negative correlation between trait mindfulness and alexithymia. Heightened attention to emotions elicited by errors may therefore strengthen executive functioning. Importantly, the attentional facet of mindfulness (present-moment awareness) was not significantly related to ERN amplitude, reinforcing the idea that the cognitive benefits of meditation are primarily affective in nature.

Furthermore, although meditators exhibited stronger ERNs, they did not show increased error positivity (Pe), a factor linked to conscious error awareness. This pattern suggests that meditators rapidly register errors but quickly disengage from emotional reactions to them. These findings suggest that increased emotional acceptance may represent one mechanism through which meditation enhances executive control (Teper & Inzlicht, 2013).

A systematic review of fifty-five studies examining mindfulness meditation and its relationship with attentional networks and executive functioning by Lodha and Gupta (2022) further clarifies the cognitive mechanisms involved. Firstly, their findings indicate that the inhibition facet of executive functioning emerged as the most consistently improved outcome, regardless of training duration or level of meditation experience. Inhibition is closely related to the control of attention, or executive attention, which plays a predominant role in detecting distraction. As the authors suggest, these improvements may reflect the intended effect of mindfulness practice of

enhancing the capacity to inhibit automatic responses to stimuli and instead sustain attention toward the object of interest. In addition to the improvements observed for sustained and executive attention, mindfulness practice has been associated with improvements in cognitive flexibility, including attentional switching abilities (Lodha & Gupta, 2022). Furthermore, expert meditators have been found to exhibit a significantly smaller attentional blink, suggesting a more efficient allocation of attentional resources during rapid information processing.

Moreover, extending these findings beyond attention and executive control, and given the close relationship between executive processes and memory functioning, preliminary evidence suggests that mindfulness meditation practice (MMP) may also influence memory-related processes. Specifically, MMP has been associated with enhanced working memory capacity and may help prevent declines in working memory performance prior to exposure to stressful stimuli. In addition, MMP has been linked to increased memory specificity, a psychological marker of mental well-being. Memory specificity represents the opposite of overgeneral memory, which has been associated with impaired social problem-solving abilities (Lodha & Gupta, 2022).

Clinical Implications and Emotional Regulation. From a clinical perspective, these neurocognitive and neuroplastic changes suggest that mindfulness meditation may have meaningful therapeutic implications, many of which appear to be mediated by improvements in executive functions and attentional control. For example, by reducing the excessive elaboration of negative stimuli, more resources are available to develop an optimal response to environmental demands. Another example is individuals with lower working memory capacity, who are more likely to suffer from emotionally intrusive thoughts and are less able to suppress them. However, mindfulness meditation is not a

skill that will indiscriminately better any disorder, as is exemplified by patients with traumatic brain injury or ongoing Alzheimer's Disease or cognitive decline (Lodha & Gupta, 2022). However, it is a practice that could enhance cognitive abilities especially valuable for patients with ADHD, based on the improved attentional skills, as well as with depression and anxiety, based on the improved ability to regulate emotions and control intrusive thoughts and rumination, and with autism spectrum disorder (ASD), improving executive performance and diminishing mood disorders by modifying functional connectivity (Trichal, 2026). It has also been found useful to prevent rather than treat cognitive decline and age related disorders.

1.2 Interoception

Definition and Conceptual Evolution of Introception. Interoception is a relatively recent concept, introduced alongside proprioception and exteroception in the early 20th century by Sherrington (1906), with its first appearance in scientific journals dating back to the 1940s (Ceunen, 2016). In his original description, Sherrington characterized interoception as relating to the body's internal surface, distinguishing it from the external surface, which is in contact with the environment and therefore considered exteroceptive. He also made a distinction between the skeletal muscle, as an area of proprioception and the viscera, which he identified as the primary site of interoceptive receptors. Nowadays, as research on the subject has expanded, the definition of interoception has evolved into a broader concept: the integration within the central nervous system (CNS) of afferent signals about the body's physiological state (Ceunen, 2016), rather than being limited solely to the viscera. Another definition of interoception proposed by Quigley et al. (2021) describes it as the combined processing

of internal and external signals, shaped by the cognitive and emotional context, to form an overall physiological representation of the body's state, encompassing both conscious and unconscious components. Conscious awareness of interoceptive signals typically emerges when homeostasis is disrupted, such as during increased respiration, elevated heart rate, or bladder fullness, or when the internal physiological balance is altered, like in nausea (Berntson & Khalsa, 2021). Through interoceptive processing, the nervous system integrates, anticipates, and interprets bodily signals, with the objective of regulating the energy required to support life, minimizing neural energetic cost. Some of the functions of interoceptive processing include regulation of ingestion and excretion, affective experience, memory and the psychological sense of self (Quigley et al., 2021).

Neutral Pathways of Interoception. The conception of visceral regulation has also evolved with time. Although it was initially described as being mainly driven by simple, low-level reflexes, current evidence shows that visceral regulation also depends on important contributions from rostral (high-order) brain regions, which generally receive a large range of ascending visceral afferents (Berntson & Khalsa, 2021). These areas include the nucleus tractus solitarius (NTS), the parabrachial nucleus, thalamus, hypothalamus, hippocampus, amygdala, insula, the somatosensory cortices, ACC, and prefrontal areas such as the orbitofrontal cortex and medial prefrontal cortex. This widespread set of ascending pathways highlights how visceral signals are continuously conveyed to multiple levels of the brain, supporting integrated processing across autonomic, emotional, and cognitive systems rather than remaining confined to simple reflex circuits. In addition to afferent (ascending) pathways conveying information about internal bodily states to the brain, efferent (descending) systems play a reciprocal

regulatory role by shaping the internal environment and modulating interoceptive afferent signaling.

The Role of the Insula in Interoception. To construct a central, high-order representation of the body status, the mid insula appears as the key integrative hub and integrator of the available information (Ceunen et al., 2016). The mid-insula receives homeostatic input from the dorsal posterior insula and, in addition, non-homeostatic afferent signals from the spinal cord through the secondary somatosensory cortex, allowing these inputs to be integrated. The mid-insula also integrates visual, auditory, and vestibular inputs. It further exchanges and combines information with the amygdala related to stimulus relevance and emotional memory, and with the hypothalamus concerning the current state of the autonomic nervous system and ongoing metabolic activity. Once this integrated representation is transmitted to the right anterior insula, where subjective time perception is also processed, interoceptive signals become part of conscious awareness, constituting conscious interoception.

Functionally, the insula shows regional specialization. The posterior insula is primarily connected with posterior temporal and parietal regions, as well as sensorimotor cortices, supporting its role in primary interoceptive processing and behavioural regulation. In contrast, the anterior insula is highly interconnected with frontal and limbic areas, contributing to emotional and cognitive functions. Across these regions, there is a general posterior-to-anterior flow of neural signals, reflecting a progressive integration of sensory information, the detection of salience, and the modulation of cognitive control and goal-directed behaviour by interoceptive and affective inputs (Craig, 2009; Menon & Uddin, 2010).

Processing within the insula is not strictly linear or hierarchical. Although information generally flows from posterior to mid to anterior regions, there is substantial interaction between these areas at multiple levels. Consequently, interoception does not arise from a single pathway but from the combined activity of a network of brain regions, forming an integrated system for representing the body's internal state. Taken together, these findings support the view that interoception is not merely a multisensory construct based on the summation of peripheral signals, but a cross-modal integrative process involving central nervous system structures. In this sense, interoception can be understood as a multimodal integration that extends beyond basic sensations, incorporating learned associations, memories, and emotions to form the subjective representation of the body's internal state (Ceunen et al., 2016).

Functional Roles of Interoception. According to Quigley et al. (2021), the process of interoception serves several functions: allostasis and homeostasis, feeding, urinary function, memory, emotional experience and the psychological sense-of self. The following sections examine each of these functions in detail.

Firstly, we will discuss allostasis and homeostasis. Interoception plays a fundamental role in maintaining bodily functioning by supporting the efficient allocation of essential resources and the elimination of waste. In this sense, the body serves as the means through which the brain achieves and sustains balance, while minimizing neural costs. It does so by coordinating processes involved in resource intake, such as ingestion, breathing, circulation, and foraging, as well as those responsible for waste removal, including breathing, circulation, elimination, and defecation. The brain also maximizes energy efficiency by a process called allostasis, through which it anticipates the body's needs, and also counts with a continuous regulatory process called homeostasis, when

error-correction is needed. Through the process of homeostasis and allostasis, the brain can work at peak efficiency (Quigley et al., 2021).

Feeding, a necessary function for energy regulation, is influenced by interoceptive signals of appetite, satiation, satiety and energy need. Nevertheless, feeding behaviour is not mediated only by the correct interpretation and attention to interoceptive signals, but also through the integration of this information with previous learnt experience and exteroceptive sensory information. The pathways through which interoceptive signals are transmitted from the periphery to the brain are the endocrine-mediated signaling and the vagus nerve, portraying gut-derived information during meals, to the caudal brainstem. Therefore, multisensory integration of interoceptive and exteroceptive stimuli is key for energy regulation, and brain regions involved in the processing of both interoception and exteroception are the orbitofrontal cortex, nucleus accumbens, and lateral hypothalamus. The hippocampus has been linked to the learned control of feeding behaviour, as lesion studies of patients with bilateral hippocampal damage show inappropriate hunger, satiation and satiety cues (Quigley et al., 2021).

Another facet of energy regulation in which interoception is involved is waste removal through urinary function. The regulation of the lower urinary tract (LUT) will rely on the integration of many signals, such as bladder fullness, feedback from the urethra, other interoceptive information, exteroceptive signals (eg: one's proximity to their home) and multisensory information. The integration of all this information will influence the perception of urinary urgency and guide behaviour accordingly (Quigley et al., 2021).

Recent evidence suggests a role of interoception in memory and learning, particularly in regards to information associated with eating behaviour. Visuospatial and contextual

memory are important when remembering the location of a food source, whilst declarative memory of facts and episodic events is needed when remembering the nutritive value of a food, as well as the features of predator and prey behaviour. The hippocampus plays a critical role in memory and learning, and emerging findings also suggest that it is sensitive to interoceptive signals related to the body's energy state, such as satiation and hunger levels. Findings suggest that interoceptive signals conveyed via meal-derived vagal signaling modulate hippocampal function to enhance the encoding of food-related memories. By integrating information about the body's energy state with visuospatial, contextual and episodic memory processes, the hippocampus supports the formation of representations of past eating experiences, guiding more adaptive and efficient future feeding behaviour.

Moreover, interoception and affective experience are closely linked. Affective experience is typically described along two dimensions: valence (ranging from pleasant to unpleasant) and arousal (from low to high activation). Studying these processes is challenging, as emotional experience is inherently subjective and often relies on self-report measures. However, recent research suggests that emotions may arise from active inference about the likely causes of interoceptive signals. In other words, the brain continuously interprets internal bodily states to construct emotional experience. One of the most compelling pieces of evidence for the role of interoception in shaping emotional and affective experience comes from the overlap in neural structures (like the insula and the cingulate cortex) involved in interoception, bodily regulation, and emotion. Additional support comes from studies showing that changes in peripheral physiology, such as heart rate or skin conductance, tend to co-vary with reported emotional states over time. However, this line of evidence remains limited, as current

methods typically offer only indirect insight into interoceptive processes, that is, show that body and emotion are linked, but not how interoceptive processes mediate that link. As a result, much of the existing evidence is correlational, which makes it difficult to draw firm conclusions about the causal role of interoceptive signals in shaping affect and emotion (Quigley et al., 2021).

The final role of interoception discussed by Quigley et al. (2021) is to allow for the psychological sense of self. In psychology, the sense of self is closely tied to body awareness. Early research mainly approached the study of body awareness through exteroceptive processes, focusing on how individuals perceive their bodies from the outside. Classic examples like the Rubber Hand Illusion show that body ownership can be shaped and even distorted by external sensory input. However, more recent approaches highlight that signals arising from within the body, such as visceral sensations, are fundamental for constructing a stable sense of self.

Evidence indicates that individuals differ in the extent to which they rely on internal versus external information when constructing body awareness. Lower interoceptive awareness has been associated with increased susceptibility to externally induced distortions of body ownership, suggesting that when internal bodily signals are imprecise, the sense of self becomes more reliant on exteroceptive input. This supports the view that interoception serves as a stabilizing anchor for self-representation. In line with this, contemporary models propose that the sense of self arises from the integration of interoceptive and exteroceptive signals. Although interoceptive information often remains outside of focal awareness, it is continuously processed and contributes to self-related processing, shaping both cognitive and emotional functioning.

Overall, interoception emerges as a complex, multi-level process involving distributed neural systems and supporting a range of functions from homeostatic regulation to emotional experience and self-representation. Notably, many of the brain regions involved, particularly the insula and ACC, overlap with those implicated in meditation, suggesting potential shared neural mechanisms.

1.3 Interoception and Meditation: Converging Evidence Across Behavioral and Neural Levels.

Meditation is associated with enhanced interoceptive processing at the behavioral level, expressed as improved detection of internal bodily signals (Farb et al., 2013), increased attentional allocation to bodily states by reducing distraction from external cues (Lodha & Gupta, 2022), and better emotion regulation behaviors that depend on bodily awareness (Ruther et al., 2026).

Both meditation and interoception show convergence across brain regions such as the insula, ACC, and prefrontal areas (Berntson & Khalsa, 2021; Fox et al., 2016). Despite this overlap, the relationship between meditation and interoceptive neural mechanisms remains insufficiently understood, particularly in terms of whether they rely on shared or distinct patterns of brain activation and a direct quantitative comparison of their neural correlates is still lacking.

1.4 FMRI

FMRI has grown and developed exponentially ever since its appearance in the early 1990s, becoming fundamental for both clinical applications as well as research in cognitive neuroscience, behaviour modification and training (Glover, 2011). Its use in

studying brain activity can reveal hidden mental processes that are inaccessible through conscious behavioural methods alone (Berkman & Falk, 2013).

Fundamentally, fMRI is a neuroimaging technique designed to detect regional and time-varying changes in brain metabolism, whether induced by cognitive tasks or occurring during resting brain activity. Compared with other neuroimaging methods used to assess brain function and metabolism, fMRI offers a balance of spatial resolution, temporal resolution, and accessibility. Common alternative modalities include Positron Emission Tomography (PET), Near-Infrared Spectroscopy (NIRS), Electroencephalography (EEG), and Magnetoencephalography (MEG). Nevertheless, fMRI is often preferred because it is non-invasive, relatively affordable, and provides good spatial resolution, making it suitable for both clinical and research applications (Glover, 2011). However, it also presents some limitations, such as low temporal resolution and the scanner's loud noise, which can interfere with studies involving auditory processing or resting-state networks (Glover, 2011).

In order to understand the mechanisms by which fMRI works, it is necessary to mention brain metabolism. All the processes of neural signaling in the brain require energy in the form of adenosine triphosphate (ATP). This molecule is mainly produced from glycolytic oxygenation of glucose, generating carbon dioxide as a byproduct. When a specific region of the brain is up-regulated by the demands of a cognitive task, it results in local increased energy requirement in the affected brain region. Instead of measuring neuronal activity directly, fMRI detects these changes in blood oxygenation levels, known as the Blood Oxygen Level- Dependent (BOLD) contrast (Glover, 2011).

In a typical task-based fMRI experiment, visual, auditory, or other stimuli are used to alternately elicit two or more distinct cognitive states while MRI volumes are acquired

continuously. Task activation is designed to induce different neural states, and activation maps are generated by comparing the signals recorded across these states. In two-condition designs, one state is defined as the experimental condition and the other as the control condition, with the objective of testing the hypothesis that the measured signals differ between the two conditions. The extent to which valid inferences can be drawn from the measured time series data depends largely on the careful design of the task. Once the images have been acquired, the resulting time series data are processed to generate maps of brain activation. Because noise can sometimes exceed the signal of interest, fMRI analyses rely on statistical tests to compare signal differences between conditions, yielding activation maps that reflect the probability that the brain states differ (Glover, 2011).

Because individual fMRI studies often involve small sample sizes, many dependent variables, and the need to correct for multiple comparisons, they can be statistically underpowered, making it difficult to detect true effects. While strategies like increasing sample size, focusing on regions of interest, or adjusting statistical thresholds can help, they are not always feasible and have important limitations. As a result, meta-analyses and other synthesis-oriented approaches are useful in these cases, because by combining data across multiple studies they increase statistical power, improve reliability, and allow researchers to identify consistent patterns of brain activity that single studies alone may miss (Cremers et al., 2017). Consequently, meta-analyses have become a crucial research tool for fMRI, allowing researchers to integrate findings across studies, establish consistency across labs and widely varying scanning procedures, and identify the brain regions most reliably engaged by particular tasks. Beyond confirming existing results, quantitative meta-analyses can also generate new hypotheses about the

neuroanatomy of cognition, emotion, and social processes, as well as test predictions derived from complementary methods such as studies of brain-damaged patients or electrophysiology (Wager et al., 2007).

A review by Ruther et al. (2026), examining structural and functional MRI studies of mindfulness-based stress reduction (MBSR), found inconsistent evidence for gray matter changes but consistent evidence for functional alterations across specific brain networks. Increased activity was observed in the superior parietal lobe, posterior cingulate cortex, and prefrontal regions. Moreover, functional connectivity studies indicated enhanced connectivity between the medial prefrontal cortex and the amygdala. The authors therefore concluded that MBSR appears to affect brain function more than structure, with increased activity and connectivity in networks related to attention, self-referential processing, and emotion regulation.

Functional neuroimaging studies have been widely used to investigate interoception as well, most commonly through cardiac paradigms (Nackley & Friedman, 2024). The most widely used tasks are the heartbeat counting task (HCT), in which participants estimate the number of heartbeats within a given time interval, and the heartbeat discrimination task (HDT), which requires judging whether external stimuli are synchronized with one's heartbeat. Beyond cardiac measures, interoception has also been assessed through respiratory tasks, typically involving the detection of changes in breathing resistance, and gastric paradigms, such as balloon distension procedures targeting the esophagus, stomach, or colon (Nackley & Friedman, 2024).

In fMRI settings, these tasks are typically implemented using block or event-related designs, in which participants are instructed to focus on internal bodily signals or, alternatively, on external control stimuli. This allows researchers to isolate brain activity

associated with interoceptive attention and perception, consistently implicating regions such as the insular cortex, ACC, and somatosensory areas. Some paradigms also involve comparing internal sensations with external cues, such as auditory tones, to assess interoceptive accuracy (Nackley & Friedman, 2024).

In the context of meditation and interoception research, where findings are derived from diverse experimental paradigms, meta-analysis provides a critical tool for identifying convergent neural activation patterns across studies and distinguishing reliable effects from study-specific variability and the reduced statistical power often associated with small sample sizes.

The present study aims to synthesize existing research and quantitatively compare the neural correlates of meditation and interoceptive processing using meta-analytic techniques. Specifically, it seeks to (1) identify convergent activation patterns across both domains, and (2) determine whether distinct neural signatures differentiate them. Based on prior literature, it is expected that both processes will consistently engage the insular cortex and ACC, while meditation-specific activity may extend to default mode and executive control networks.

2. Methods

To conduct this study, we applied a coordinate- based ALE meta-analytic approach, using the specific reported brain activation peaks (foci) of the included studies, to obtain a synthesis of the findings. We ran three ALE analyses addressing the neural activation

1. during meditative tasks
2. during interoceptive tasks
3. comparing the activation between both, doing a conjunction and subtraction analyses to identify shared and distinct activation patterns across both constructs.

The literature search and study selection were carried out following the PRISMA 2020 guidelines for systematic reviews and meta-analyses, together with current best-practice recommendations for neuroimaging meta-analytic studies. To minimize selection bias and ensure the quality of included studies, the entire procedure was independently verified by two investigators, in line with current guidelines.

2.1 Study Selection

Selection of Meditation studies. For the studies on meditation, a systematic literature search was conducted on 29 January 2025. Database-specific search strategies were applied across platforms to account for differences in indexing and search syntax. As for PubMed, the string was the following: ((fMRI) AND ((meditation) OR (mindfulness))) ("magnetic resonance imaging"[MeSH Terms] OR ("magnetic"[All Fields] AND "resonance"[All Fields] AND "imaging"[All Fields]) OR "magnetic resonance imaging"[All Fields] OR "fmri"[All Fields]) AND ("meditate"[All Fields] OR "meditated"[All Fields] OR "meditating"[All Fields] OR "meditation"[MeSH Terms]

OR "meditation"[All Fields] OR "meditations"[All Fields] OR "meditation s"[All Fields] OR "meditational"[All Fields] OR "meditative"[All Fields] OR "meditator"[All Fields] OR "meditators"[All Fields] OR ("mind s"[All Fields] OR "minded"[All Fields] OR "mindful"[All Fields] OR "mindfulness"[MeSH Terms] OR "mindfulness"[All Fields] OR "minding"[All Fields] OR "minds"[All Fields])), resulting in an output of 1182 studies. For Web of Science, 519 papers resulted from the following search string: (ALL=(fMRI)) AND (ALL=(meditation) OR ALL=(mindfulness)), and finally, 1084 from PsychNet with the string: Any Field: fMRI *AND* Any Field: meditation *OR* Any Field: mindfulness.

Across all databases, a total of 2,785 records were retrieved and imported into Rayyan for screening.

Rayyan is a web-based tool designed to support the screening and selection stage of systematic reviews and meta-analyses (Ouzzani et al., 2016). It lets researchers import references from several databases, detect and remove duplicates, and manage studies through the different phases of the review process. A key feature is that it allows multiple reviewers to screen titles and abstracts independently and in a blinded way, which helps reduce selection bias and improves the reliability and transparency of study selection. It also enables users to tag studies based on inclusion and exclusion criteria, compare decisions between reviewers, and resolve disagreements in a structured way. Because of these functions, Rayyan is widely used in evidence synthesis and is useful for PRISMA-compliant systematic reviews and meta-analyses.

After automatic and manual duplicate detection, 745 records were flagged as potential duplicates, of which 370 were removed, from the total of 2785 imported into Rayyan. A further 21 records were confirmed as non-duplicates and retained. Ambiguous cases (n

= 354) were manually reviewed and resolved.

After removing duplicates, the literature search produced an initial pool of 2415 records. These studies were independently screened in a blinded manner by two investigators at the abstract level, resulting in the exclusion of articles that failed to meet one or more of the predefined inclusion criteria: (1) scientific papers published in English; (2) empirical fMRI studies, thereby excluding reviews, meta-analyses, behavioural studies, and studies using other neuroimaging modalities (e.g., PET); (3) studies involving adult participants (age range: 18–65 years); (4) studies including healthy, non-clinical, and drug-free participants; (5) studies assessing brain activity during meditation or mindfulness-based instructions, defined as contemplative practices involving focused attention, open monitoring, or related meditative states; (6) studies reporting whole-brain analyses in standard stereotactic space (Talairach or Montreal Neurological Institute), excluding region-of-interest (ROI) or small volume correction (SVC) analyses due to violations of the assumption underlying ALE meta-analysis that each voxel has an equal a priori probability of activation; and (7) studies reporting coordinates of brain activations for at least one of the following contrasts of interest: (i) expert meditators versus baseline or non-meditative control conditions, (ii) non-expert meditators versus baseline or non-meditative control conditions, and (iii) expert versus non-expert meditators.

Following title and abstract screening of the initial pool of 2415 records, 82 studies were identified as potentially relevant and subsequently retrieved in full text for detailed eligibility assessment. When potentially eligible studies lacked key information, such as activation coordinates for the relevant contrast, the authors were contacted to request the missing data. The full text screening led to the exclusion of articles that didn’t fulfil one

or more of the previously mentioned inclusion criteria, or in case we couldn't get the coordinates after contacting the authors. A final pool of 14 studies was included in the activation analysis, yielding 14 experiments, 328 foci, and 365 participants. Only four studies were available for the deactivation analysis, falling below the recommended minimum number of experiments; consequently, this analysis was not reported. **Figure 1** presents a detailed flow diagram of the literature search and study selection process in accordance with the PRISMA 2020 guidelines (Page et al., 2021a,b).

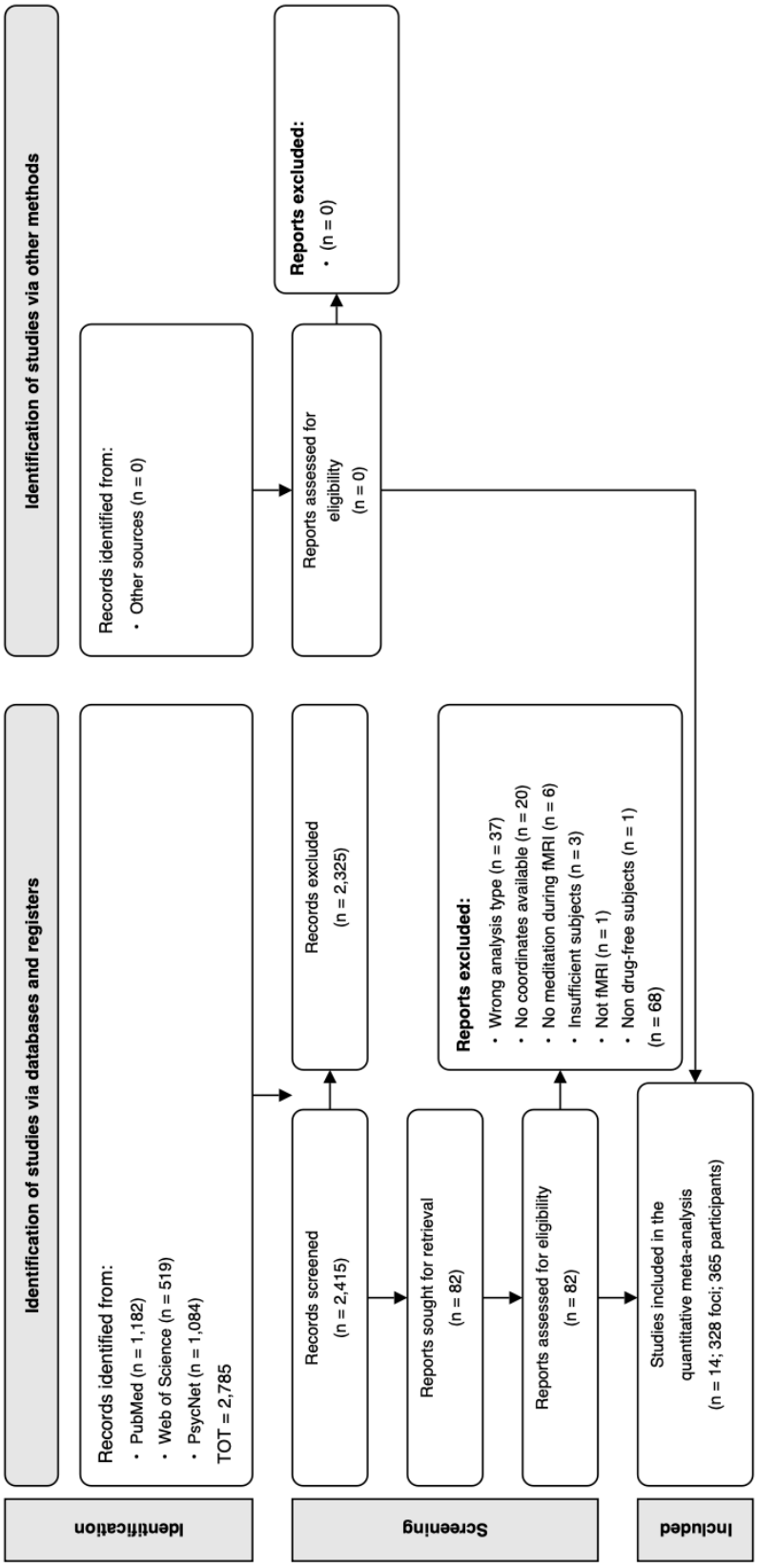

Fig. 1. PRISMA 2020 flowchart of the literature search and selection process for the “meditation” ALE meta-analysis.

For all included meditation studies, relevant data were systematically extracted following PRISMA guidelines. Extracted variables included sample characteristics (number of participants, mean age of meditators and controls where available, and sex distribution), experimental characteristics (meditation task type, stimuli used, and reported contrasts), and neuroimaging results (peak activation coordinates in x, y, z space and number of reported foci per contrast). In addition, information regarding the stereotactic space used for reporting coordinates (Montreal Neurological Institute [MNI] or Talairach space) was recorded.

Selection of Interoception studies. The selection of Interoception studies was based on both our own systematic screening and a subset of previously identified papers provided by Salvato et al. (2019).

In their original work, Salvato et al. (2019) conducted a systematic search of peer-reviewed functional neuroimaging studies using the BrainMap database (queried via Sleuth software, Version 2.0.3), complemented by searches in MEDLINE, PubMed, and relevant life-science journals. The search was not restricted to cardioception studies but included a broader range of interoceptive tasks. In contrast, our own search was conducted primarily using PubMed.

The search string was the following for both procedures: “fMRI” <OR>“functional neuroimaging” <OR>“PET” <OR>“neural basis” <OR>neural correlate <AND>“interoception” <OR>“cardioception” <OR>“visceral perception” <OR>“body emotions” <OR>“bodily emotions” <OR>“heartbeat” <OR>“heartbeat detection.”

The inclusion criteria required for studies entering the interoception meta-analysis were as follows: (a) description of standard Talairach and Tournoux (1988), or MNI coordinates (to enable comparison of reported peak activation across studies); (b)

samples composed of unmedicated and untrained healthy adults; (c) corrected thresholds of significance established at a whole-brain level; (d) measurement of regional cerebral blood flow (e.g., through PET) or blood oxygenation (e.g., through fMRI); and (e) tasks tapping core processes of interoception or body ownership without assessing related high-level processes or pursuing more specific goals (such as correlations and/or interactions with other psychological constructs or demographic features) (Salvato et al., 2019).

Following Salvato et al. (2019), the initial screening yielded 40 eligible studies. Of these, three were excluded by our team due to inappropriate task design and an additional three due to the use of unsuitable contrasts of conditions. Our independent search identified 139 studies, of which 89 were excluded based on title and abstract screening. The remaining 50 full-text articles were assessed for eligibility, resulting in the exclusion of 48 studies. Ultimately, a final sample of 36 interoception studies was included in the analysis. **Figure 2** illustrates the study selection process in accordance with PRISMA 2020 guidelines (Page et al., 2021a,b).

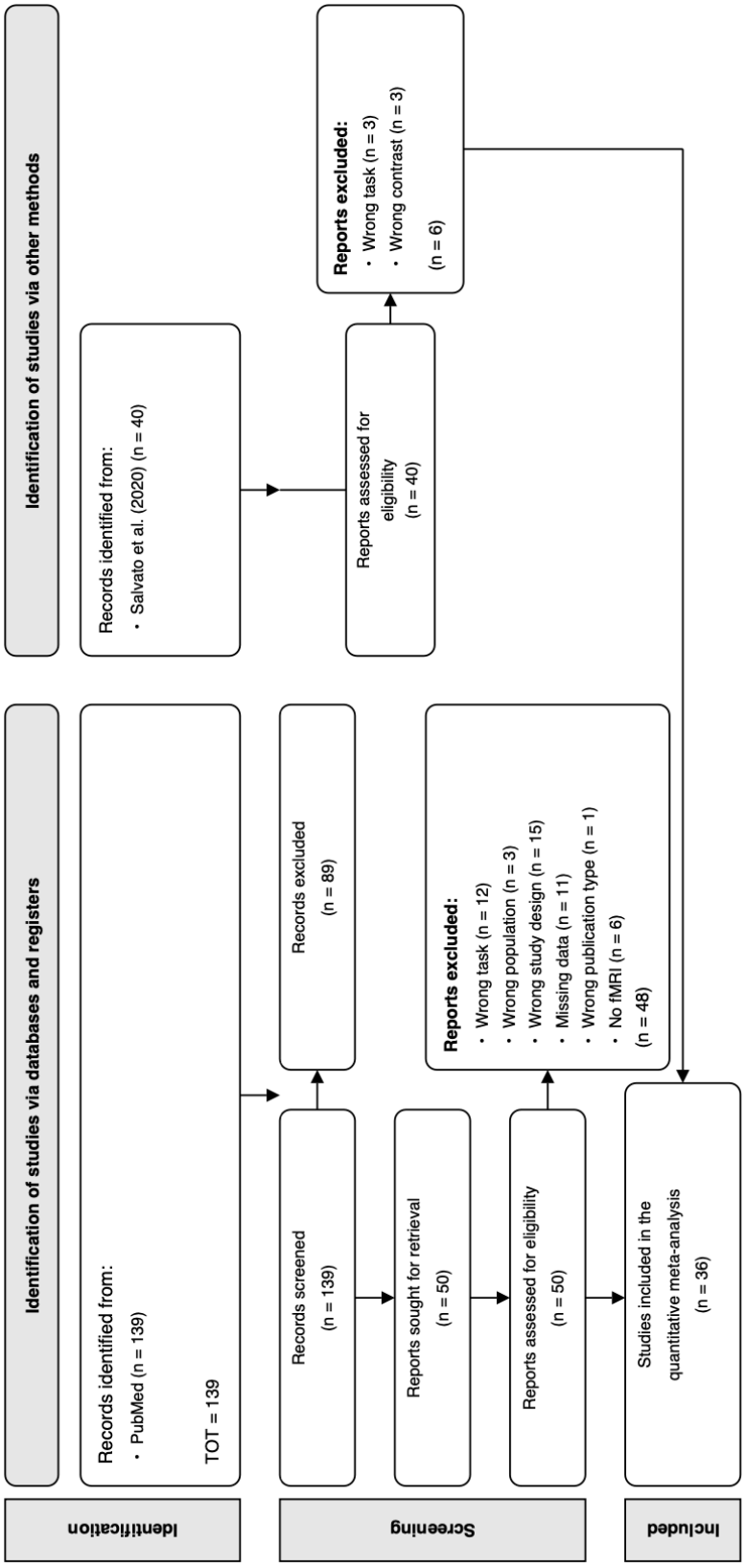

Fig. 2. PRISMA 2020 flowchart of the literature search and selection process for the "interoception" ALE meta-analysis.

For interoception studies, relevant data were extracted including sample size, mean age of participants, task type and contrasts type. In addition, stereotactic coordinates (x, y, z), number of activation foci per contrast, and coordinate space (Talairach or MNI) were recorded. The resulting dataset was then subjected to an ALE meta-analysis, allowing for subsequent comparison with the meditation dataset.

2.2 Analyses

Prior to conducting the ALE analyses, all coordinate files were reviewed and corrected where necessary by cross-checking them against the original source tables.

Three ALE analyses were conducted using GingerALE 3.0.2 software: (i) a meta-analysis of meditation studies, (ii) a meta-analysis of interoception studies, and (iii) comparative analyses examining both overlapping and differential neural activation patterns between the two meta-analyses. We followed the revised ALE algorithm by Eickhoff et al. (2012). In each ALE analysis, spatial convergence across studies was assessed by testing whether the observed clustering of activation foci exceeded that expected by chance. To this end, all reported activation coordinates were modeled as three-dimensional Gaussian probability distributions centered at the respective peak locations (Eickhoff et al., 2009). Coordinates were originally reported in MNI space or converted to MNI coordinates using transformation routines implemented in GingerALE. To account for spatial uncertainty associated with each focus, the width of the probability distributions was adjusted as a function of sample size, such that studies with larger samples contributed more precise spatial estimates.

Within each experiment, the probability distributions of all reported foci were combined

to generate modeled activation (MA) maps (Turkeltaub et al., 2012). These MA maps were then aggregated across experiments by computing voxel-wise ALE scores, reflecting the likelihood of convergence in activation across independent studies at each spatial location (Turkeltaub et al., 2002).

To determine whether observed convergence exceeded that expected under spatial independence, ALE scores were compared against an empirically derived null distribution representing random spatial association between experiments (Eickhoff et al., 2012). This null distribution was generated through permutation testing, in which voxels were randomly sampled from each MA map and ALE values were recomputed across a large number of iterations to approximate chance-level convergence.

In accordance with current methodological guidelines (Eickhoff et al., 2016), statistical significance was assessed using a cluster-level family-wise error correction (cFWE) at $p < 0.05$, with an initial cluster-forming threshold of $p < 0.001$ (uncorrected). Voxels exceeding this threshold were interpreted as showing significant convergence across experiments, reflecting consistent activation associated with the process of interest.

Finally, resulting ALE maps from the meditation and interoception analyses were used for conjunction and contrast analyses to identify shared and distinct patterns of neural activation using GingerALE software.

The conjunction analysis was performed to identify overlapping activation patterns between the two meta-analyses. This was achieved by computing the voxel-wise minimum of the thresholded ALE maps, thereby highlighting regions showing consistent convergence across both datasets. Prior to the contrast analyses, the meditation, interoception, and pooled ALE maps were regenerated using a common MNI mask and grid to avoid image-space mismatches. Bidirectional contrasts

(meditation > interoception and interoception > meditation) were then computed using 1,000 permutations.

In contrast, difference (subtraction) analyses were conducted to examine domain-specific effects between meditation and interoception. These analyses were implemented as direct voxel-wise comparisons between the two ALE maps, yielding contrast images that reflect regions showing greater convergence in one dataset relative to the other (and vice versa). Resulting subtraction values were transformed into Z-scores to facilitate interpretation of the observed differences (Eickhoff et al., 2011). For both conjunction and contrast analyses, statistical significance was assessed using a false discovery rate correction assuming independence or positive dependence (FDRpID) at $p < 0.05$, with a minimum cluster extent of 50 mm^3.

GingerALE (Version 3.0.2) is a software package developed within the BrainMap project for conducting coordinate-based activation likelihood estimation (ALE) meta-analyses of neuroimaging data. It provides a standardized framework for synthesizing results from functional neuroimaging studies by statistically evaluating the convergence of reported activation foci across experiments in a common stereotactic space (MNI or Talairach). The software implements the ALE algorithm by modeling activation coordinates as spatial probability distributions and computing voxel-wise estimates of convergence, while incorporating appropriate random-effects inference and correction for multiple comparisons. GingerALE also includes tools for coordinate transformation, data preprocessing, and the execution of permutation-based statistical testing, making it a widely used platform for identifying consistent patterns of brain activation across studies (Laird et al., 2011; Eickhoff et al., 2012).

3. Results

3.1 Meditation

In the meditation dataset, several coordinates were identified as extraction/OCR errors and were corrected accordingly. The final meditation coordinate file comprised 328 foci from 14 experiments involving 365 participants.

The ALE analysis of meditation-related activations revealed one significant cluster located in the right ACC, extending into the medial frontal gyrus (MFG) (**Table S1**). The peak of convergence was observed at MNI coordinates (12, 36, 10), with a maximum ALE value of 0.0233 ($Z = 5.08$, $p = 1.88 \times 10^{-7}$). The cluster was relatively small (896 mm^3) and extended from (8, 30, 6) to (16, 46, 22), with two local peaks. Anatomically, the cluster was predominantly situated within the limbic lobe (83.3%), specifically the ACC, with additional involvement of the MFG. Cytoarchitectonically, the cluster primarily encompassed Brodmann areas (BA) 32 (52.4%) and 24 (31%), with a smaller contribution from BA9 (16.7%).

Table S1. Results of the single ALE meta-analyses. For each meta-analysis, the following information is reported: cluster ID, anatomical label, ALE score, and MNI coordinates.

		Meditation			
1	Anterior cingulate cortex	0.02325580	12	36	10
1	Medial frontal gyrus	0.01505922	10	44	20

Note. The meditation ALE meta-analysis included 14 experiments, 328 foci, and 365 participants.

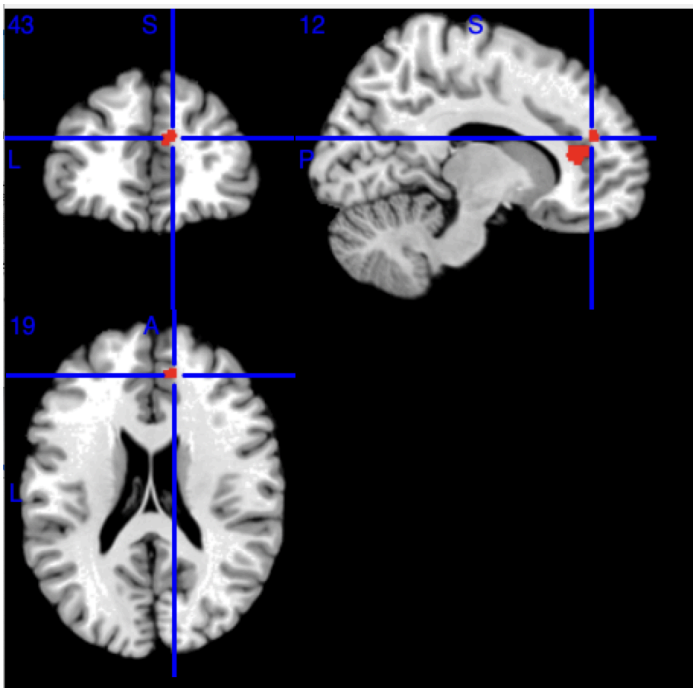

Fig. 3. ALE cluster associated with meditation

3.2 Interoception

The interoception ALE included 80 experiments, 740 foci, and 1604 participants. The meta-analysis of studies on interoception revealed significant convergence in a bilateral cortical network including the insular cortex, the precentral and postcentral gyri, the inferior frontal cortex (pars opercularis), and the Rolandic operculum. In addition, significant convergence was observed in the SMA, middle cingulate cortex (MCC), left inferior parietal cortex, and left supramarginal gyrus (**Table S2**).

Four significant ALE clusters were identified. The largest cluster (Cluster 1; 10,016 mm^3) was located in the right insular cortex and adjacent claustrum, extending into the precentral gyrus and inferior frontal gyrus. This cluster was centered at MNI coordinates (43.8, 5.1, 6.2) and exhibited the highest convergence across studies, with a peak ALE value of 0.0487 ($Z = 7.22$, $p = 2.54 \times 10^{-13}$) at (42, 8, 0). The cluster was primarily localized within Brodmann area (BA) 13.

A second cluster (Cluster 2; 6,480 mm^3) was centered on the medial frontal wall (1.2, -0.5, 47.4), encompassing the SMA and MCC bilaterally. The peak convergence was observed at (4, -2, 50) with an ALE value of 0.0344 ($Z = 5.65$, $p = 8.15 \times 10^{-9}$). This cluster mainly involved BA 6 and BA 24.

The third cluster (Cluster 3; 5,392 mm^3) was located in the left insular cortex and adjacent claustrum, extending into the precentral gyrus and rolandic operculum. Centered at (-41.5, 3.7, 6.3), the cluster showed a peak ALE value of 0.0385 ($Z = 6.12$, $p = 4.76 \times 10^{-10}$) at (-36, 4, 8), with most voxels localized within BA 13.

The fourth cluster (Cluster 4; 1,816 mm^3) was situated in the left inferior parietal cortex, extending into the postcentral and supramarginal gyri. The cluster was centered at (-56.8, -28.7, 32.3) and reached a peak ALE value of 0.0295 ($Z = 5.05$, $p = 2.25 \times 10^{-7}$) at (-56, -26, 34). The majority of this cluster was located within BA 40.

Table S2. Results of the single ALE meta-analyses. For each meta-analysis, the following information is reported: cluster ID, anatomical label, ALE score, and MNI coordinates.

	Interoception							
1	Insula	0.04867187				42	8	0
1	Rolandic operculum	0.03893637				60	2	12
1	Insula	0.03056327				34	12	16
1	Insula	0.02606532				38	-12	10
1	Insula	0.02543347				36	0	18
1	Superior temporal pole	0.01876525				54	14	-6
2	Supplementary motor area	0.03438696				4	-2	50
2	Supplementary motor area	0.03037523				10	-6	58
2	Middle cingulate cortex	0.02788029	-8	-6	38			
2	Middle cingulate cortex	0.02634288	-2	16	36			
3	Insula	0.03845229	-36	4	8			
3	Rolandic operculum	0.03449393	-52	4	8			
3	Insula	0.02066385	-34	-6	14			
3	Insula	0.0197253	-44	10	-6			
4	Supramarginal gyrus	0.02946381	-56	-26	34			
4	Postcentral gyrus	0.0177487	-48	-18	38			

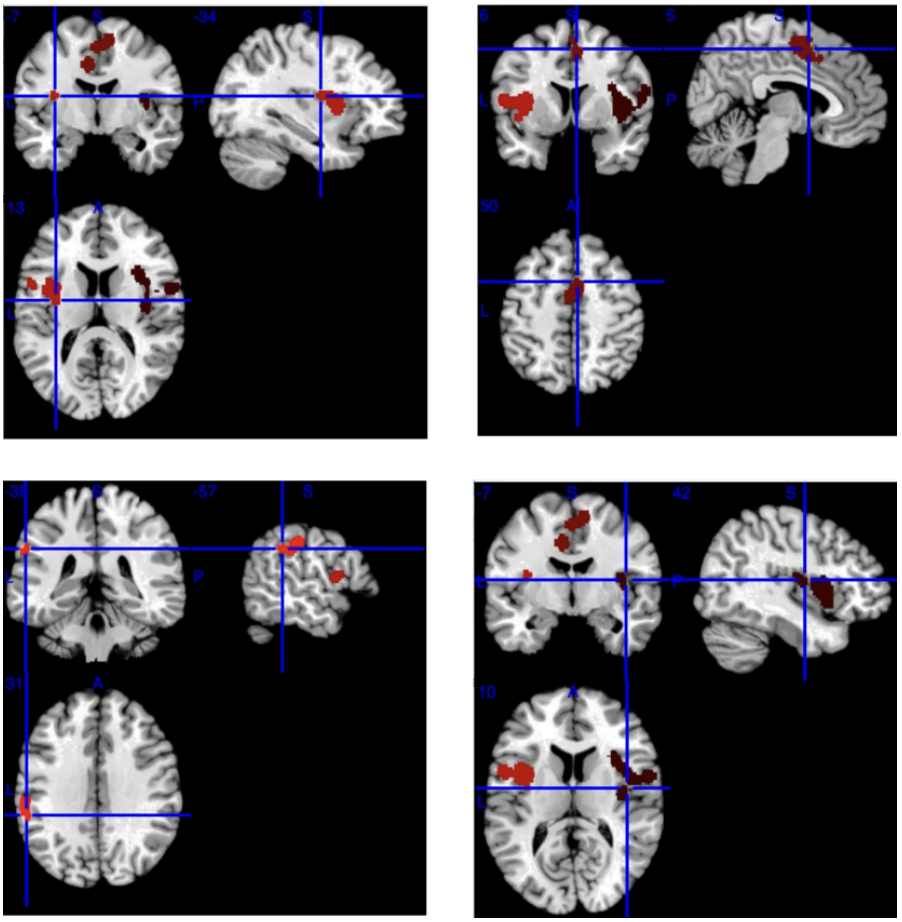

Fig. 4. ALE clusters associated with interoceptive processing

3.3 Convergence and Contrast Analyses

To directly compare the neural correlates of meditation and interoception, a formal GingerALE contrast analysis was performed using 1,000 permutation tests. The meditation, interoception, and pooled ALE maps were generated using a common MNI mask and grid to ensure spatial compatibility.

The pooled ALE analysis of the combined meditation and interoception literature revealed five significant clusters after cluster-level FWE correction, indicating overall convergence across the included studies rather than statistically significant overlap between the two domains. The strongest convergence was found in bilateral insular regions, extending into the claustrum, precentral gyrus, and inferior frontal cortex.

Additional significant convergent clusters emerged in the medial frontal/SMA-cingulate region, the left inferior parietal and postcentral cortex, and the ACC.

The formal conjunction analysis did not identify any significant voxel-wise overlap between the meditation and interoception ALE maps.

In addition, the directional contrast analysis did not reveal any significant clusters for either meditation > interoception or interoception > meditation at the selected statistical threshold ($p < .05$). Specifically, the meditation > interoception contrast showed no significant voxels, with a maximum observed Z value of 0.136 located near MNI coordinates (-34, -18, -20). Similarly, the interoception > meditation contrast revealed no significant voxels, with a maximum observed Z value of 0.148 located near MNI coordinates (20, -36, -6).

Therefore, formal contrast analysis failed to identify statistically reliable differences between interoception and meditation. Although preliminary and exploratory in nature, these findings suggest shared/convergent recruitment rather than a clear dissociation between the two domains.

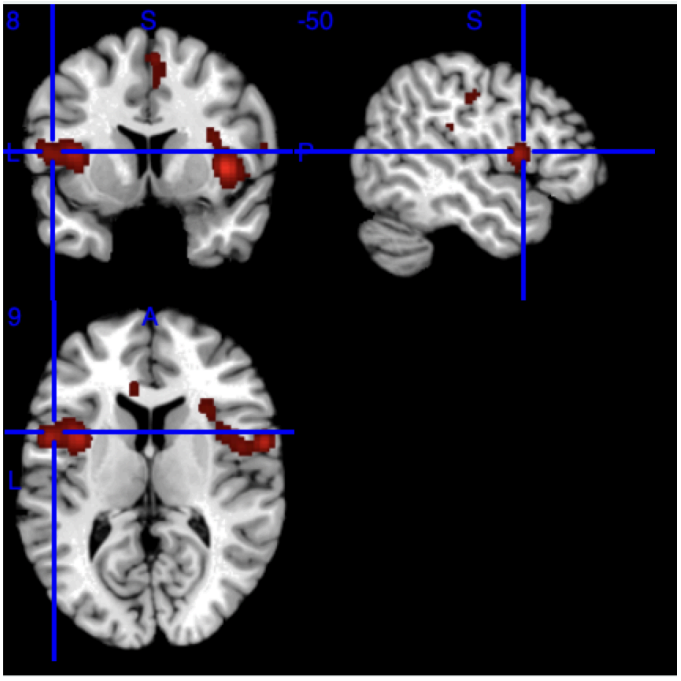

Fig. 5. Pooled ALE meta-analysis of meditation and interoception**.** Thresholded cluster-level FWE-corrected ALE map ($p < .05$; cluster-forming threshold $p < .001$), displayed on anatomical template. The map illustrates overall spatial convergence across the combined meditation and interoception literature.

4. Discussion

We performed a coordinate-based meta-analysis of previous fMRI studies to identify the brain regions consistently associated with meditation and interoceptive processing. Given the conceptual and functional overlap between these two domains in terms of internal attention and bodily awareness, we also assessed the degree of convergence and specificity across their neural bases, in order to clarify the extent to which meditative states and interoceptive attention recruit overlapping or dissociable brain regions.

4.1 Meditation

The present ALE analysis of meditation-related activations revealed a single significant cluster located in the right ACC, extending into the MFG and encompassing portions of BA 32, BA 24, and BA 9.

This finding is consistent with previous research identifying the ACC as one of the brain regions most reliably associated with mindfulness meditation and meditation-related improvements in attentional functioning (Tang et al., 2016). The ACC is thought to play a central role in executive attention and cognitive control by detecting conflicts between competing streams of information processing and facilitating the allocation of attentional resources (Tang et al., 2016). Within the context of meditation, such processes may support the maintenance of attention on a chosen object, such as the breath or bodily sensations, while monitoring and disengaging from distracting thoughts. Moreover, the involvement of the MFG (including BA9) suggests engagement of sustained attentional control and distraction monitoring processes (Demeter et al., 2011), both crucial for maintaining focus during meditation.

4.2 Interoception

The meta-analysis of interoception studies showed consistent convergence across a bilateral cortical network involving the insula, precentral and postcentral gyri, inferior frontal gyrus (pars opercularis), and rolandic operculum. Additional significant convergence was found in the SMA, MCC, as well as the left inferior parietal lobule and left supramarginal gyrus.

The prominent activation of the insular cortex, especially the anterior insula (BA 13) is coherent with its recognized role as a key hub in self awareness and own body signal representation (Craig, 2009; Ceunen et al., 2016). Importantly, the activation of primary somatosensory (postcentral gyrus) and motor regions (precentral gyrus) suggests that interoceptive processing engages broader sensorimotor networks involved in the representation and monitoring of bodily states (Quigley et al., 2021).

The activation of the rolandic operculum and left supramarginal gyrus supports findings by Blefari et al. (2017), suggesting a role in integrating interoceptive and exteroceptive signals for body representation and interoceptive awareness. Extending this interpretation, the inferior parietal lobule may reflect a broader integrative hub supporting higher-order representations of bodily states by combining somatosensory and interoceptive information, and guiding attention towards behaviourally relevant internal sensations (Igelström & Graziano, 2017).

The inferior frontal gyrus might be implicated in knowledge-based appraisal of one's own emotional and bodily states (Terasawa et al., 2011), reflecting an additional higher-order step in the integration of interoceptive information beyond pure visceral sensation. In this sense, it supports the view of interoception as involving memories and emotions in the processing of the internal body state (Teresawa et al., 2011).

The involvement of the SMA in interoception-related paradigms may reflect its role in the selection and preparation of internally generated actions (Nachev et al., 2008). As the SMA is particularly engaged when actions are guided by internal rather than external cues, its activation may indicate a functional role in transforming internally generated signals, including bodily states, into potential action plans (Nachev et al., 2008). This interpretation is consistent with contemporary conceptualizations of interoception as an active and dynamic process. Rather than solely reflecting the passive monitoring of afferent bodily signals, interoception also involves processes that guide responses to internal states, which can subsequently influence future interoceptive input (Berntson & Khalsa, 2022). Furthermore, given the known anatomical and functional connectivity between the SMA and primary motor cortex (Nachev et al., 2008), their convergent involvement across interoception studies may indicate the engagement of a broader motor hierarchy supporting the translation of internal bodily states into action preparation and execution.

In the context of interoception, the MCC has been suggested to be involved in allostasis (Santamaría-García et al., 2025), using interoceptive information to guide behaviour. Specifically, it may contribute to evaluating the relevance of bodily signals and coordinating appropriate responses to maintain physiological stability. The activation observed in the present meta-analysis may therefore reflect a role of the MCC in linking the monitoring of bodily states with the selection and preparation of adaptive actions.

4.3 Convergence and Contrast Analyses

The pooled ALE analysis revealed convergence between meditation and interoception within a core insula–cingulate/medial frontal network, a system consistently implicated

in interoceptive awareness (Craig, 2009), salience processing (Menon & Uddin, 2010), and the integration of bodily states with higher-order regulatory control to regulate the physiological state proactively (Barrett & Simmons, 2016). This overlap suggests that both meditation and interoceptive paradigms recruit shared neural substrates involved in monitoring internal bodily signals and supporting adaptive regulation of internal states. Importantly, the formal conjunction analysis did not reveal significant voxel-wise overlap between the two separate ALE maps. Therefore, the pooled findings should be interpreted as descriptive evidence of a partially shared neural network, rather than as formal statistical evidence of overlap or dissociation between the two domains. Moreover, formal contrast analyses did not reveal any statistically significant differences between meditation and interoception in either direction. Although exploratory in nature, this absence of dissociable clusters suggests that, at the level of meta-analytic convergence, meditation does not recruit neural systems that are reliably distinct from those engaged during interoceptive processing. Instead, both domains appear to rely on a partially shared functional architecture centred on midline and insular regions. However, the pooled findings should be interpreted as descriptive evidence of a partially shared neural network, rather than as formal statistical evidence of overlap or dissociation between the two domains.

From a theoretical perspective, these findings may reflect the close coupling between contemplative practices and interoceptive processing, particularly given that many forms of meditation explicitly involve sustained attention to internal bodily states (Bishop et al., 2004). The lack of significant results in the contrast analysis suggests that meditation may act on the same neural systems involved in everyday interoceptive awareness, rather than relying on a separate brain network.

5. Conclusion and Future Directions

The present study used coordinate-based meta-analysis to investigate the neural correlates of meditation and interoceptive processing, and to directly assess the degree of overlap between these domains. Consistent with previous literature (Berntson & Khalsa, 2021; Fox et al., 2016), meditation was associated primarily with convergence in the ACC and medial frontal regions involved in attentional control and self-regulation. In contrast, interoception engaged a broader network including the insula, sensorimotor cortices, inferior frontal cortex, SMA, MCC, and parietal regions implicated in bodily representation and awareness.

Importantly, the pooled ALE analysis of the combined meditation and interoception datasets revealed convergence within an insula–cingulate/medial frontal network, while formal contrast analyses failed to identify statistically significant differences between the two domains. Although exploratory and descriptive, these findings suggest that meditation and interoception may rely on partially shared neural mechanisms rather than clearly dissociable systems.

One possible explanation for the lack of difference between the two constructs in the comparison analysis is that many meditation practices explicitly require attention to internal bodily sensations, particularly the breath, heartbeat, or other bodily experiences, despite the tasks being different to those in interoceptive studies. From this perspective, meditation may represent a structured way of engaging interoceptive attention. Previous empirical work has proposed that mindfulness meditation enhances awareness of bodily signals and promotes greater sensitivity to interoceptive information (Farb et al., 2015). The present findings provide meta-analytic support for this view by demonstrating

convergence within neural systems commonly associated with interoceptive awareness and self-regulation.

At the same time, the broader network observed for interoception suggests that interoceptive processing extends beyond the neural mechanisms consistently recruited during meditation. Regions such as the inferior parietal lobule, supramarginal gyrus, rolandic operculum, and sensorimotor cortices may reflect processes related to multisensory integration, body representation, and the monitoring of physiological states that are not always explicitly required in meditation paradigms. This suggests that meditation may engage a subset of the wider interoceptive system, particularly regions involved in attentional monitoring and awareness of bodily states.

To our knowledge, this is the first meta-analysis to directly compare the neural correlates of meditation and interoception using ALE methodology. Although a conceptual link between these domains has been widely proposed, evidence for their neural overlap has remained largely indirect. By examining both convergence and divergence across the two literatures, this study provides quantitative evidence for a shared neurobiological basis in terms of pooled convergence across studies, rather than statistically defined overlap between domains.

Several limitations should be noted. The meditation literature included fewer experiments than the interoception literature, which may have reduced statistical power and limited the detection of meditation-specific effects. In addition, both domains are methodologically heterogeneous. Interoceptive studies differ in the bodily signals examined, while meditation studies vary in technique, level of expertise, and attentional focus. As a result, the observed patterns may reflect processes common across broad

forms of meditation and interoceptive attention rather than effects specific to particular practices.

Future research should examine whether different forms of meditation, such as focused attention, open monitoring, and body-scan practices, show distinct patterns of overlap with interoceptive processing. Finally, future meta-analyses could benefit from separating different dimensions of interoception, such as accuracy, sensibility, and awareness, to determine whether specific aspects of bodily processing are more closely linked to meditation-related neural activity.

Overall, the present findings suggest that meditation and interoception are closely related functions supported by overlapping neural networks involved in bodily awareness, attentional regulation, and the adaptive control of internal states. In particular, the results point to a common neural basis for directing attention toward the body, even when the task demands differ. Although meditation and interoceptive paradigms are not identical, the first one being an internally guided practice and the other typically an externally instructed focus on bodily signals, both appear to engage similar systems when attention is oriented toward internal bodily experience. This convergence in the pooled dataset suggests that meditation may, at least in part, operate as a structured way of cultivating bodily awareness through mechanisms that closely resemble those recruited during explicit interoceptive attention tasks.

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Appendix

Supplementary Table 1. Overview of the studies included in the quantitative ALE meta-analysis on the neural bases of meditation in healthy individuals.

Study	Sample	Mean Age	Type of task	Contrast	Foci	Space
Saraei et al. (2022)	28	NR	Guided body-scan meditation; Dhikr; thinking about God	Meditation-related condition vs resting-state/network baseline	10	MNI
Guleria et al. (2013)	14	NR	SOHAM meditation	SOHAM meditation > control	4	MNI
Lutz et al. (2016)	40	NR	Mindful self-awareness task	Mindful self-awareness / FEEL > cognitive self-reflection / THINK	6	MNI
Hasenkamp et al. (2012)	14	NR	Focused attention to breath	Meditation-related attentional state > mind wandering	1	MNI
Garrison et al. (2015)	46	NR	Meditation-related neurofeedback / mindfulness task	Meditation-related condition > control/baseline	6	MNI
Hernandez et al. (2018)	46	NR	Sahaja Yoga meditation / mental silence	Meditation condition > control/baseline	2	MNI
Holzel et al. (2007)	30	NR	Vipassana / mindfulness meditation	Mindfulness meditation vs arithmetic/control; meditators vs non-meditators	14	MNI

Lee et al. (2012)	44	NR	Focused-attention and loving-kindness meditation	Meditation-related condition > comparison/control condition	14	MNI
Baerentsen et al. (2010)	31	NR	Meditation onset / continuous meditation	Meditation onset or continuous meditation > baseline/rest	13	MNI
Engstrom et al. (2010)	8	NR	Silent mantra meditation	Silent mantra meditation > control/word condition	9	MNI
Manna et al. (2010)	16	NR	Theravada focused-attention and open-monitoring meditation	FA meditation > rest; OM meditation > rest	34	MNI
Singer et al. (2015)	15	NR	Compassion-based emotion regulation / meditation	Compassion meditation/ regulation > comparison conditions	158	MNI
Xu et al. (2014)	14	49	Nondirective Acem meditation	Nondirective meditation > rest; nondirective meditation > concentrative practice	43	MNI
Hernandez et al. (2015)	19	NR	Sahaja Yoga meditation / mental silence	Meditation period > control relaxation condition	14	MNI

Supplementary Table 2. Overview of the studies included in the quantitative ALE meta-analysis on the neural bases of interoception in healthy individuals.

Study	Sample	Mean Age	Type of task	Contrast	Foci	Space
Araujo et al. (2015)	19	22.5	Questions about personality trait, biographical facts, interoception and exteroception	Interoceptive attention > exteroceptive attention	27	MNI
Avery et al. (2015)	20	28	Interoceptive task requiring focusing on heart, stomach and bladder	Interoceptive attention > exteroceptive attention	26	TAL
Bauer et al. (2014)	34	35.58	Attention directed to touch sensation and spontaneous sensation to left/right thumb	Touch sensation > rest (right thumb)	3	MNI
	34	35.58	Attention directed to touch sensation and spontaneous sensation to left/right thumb	Spontaneous sensation > rest (right thumb)	5	MNI

	34	35.58	Attention directed to touch sensation and spontaneous sensation to left/right thumb	Touch sensation > spontaneous sensation (right thumb)	2	MNI
	34	35.58	Attention directed to touch sensation and spontaneous sensation to left/right thumb	Spontaneous sensation > touch sensation (right thumb)	6	MNI
	34	35.58	Attention directed to touch sensation and spontaneous sensation to left/right thumb	Touch sensation > rest (left thumb)	4	MNI
	34	35.58	Attention directed to touch sensation and spontaneous sensation to left/right thumb	Spontaneous sensation > rest (left thumb)	3	MNI

	34	35.58	Attention directed to touch sensation and spontaneous sensation to left/right thumb	Touch sensation > spontaneous sensation (left thumb)	4	MNI
	34	35.58	Attention directed to touch sensation and spontaneous sensation to left/right thumb	Spontaneous sensation > touch sensation (left thumb)	3	MNI
Becker et al. (2015)	24	22.9	Viewing pictures of beverages and chairs in thirst condition and no-thirst condition	(BeveragesThirst>ChairsThirst) vs (BeveragesNo-thirst> ChairsNothirst) interaction	9	MNI
Binks et al. (2014)	8	23–31 years	Air hunger task	Air hunger > rest	13	MNI
Blefari et al. (2017)	16	24.5	Heartbeat monitoring task	Interoceptive attention > control	6	MNI
Brannan et al. (2001)	9	28	Inhalation of CO2, inhalation of O2, paced breathing (PB)	CO2 > O2	23	TAL

			room air and rest			
	9	28	Inhalation of CO2, inhalation of O2, paced breathing (PB) room air and rest	CO2 > PB	12	TAL
	9	28	Inhalation of CO2, inhalation of O2, paced breathing (PB) room air and rest	CO2 > rest	11	TAL
Caseras et al. (2013)	52	21.72	Phobic symptom provocation task and heartbeat monitoring task	Interoceptive attention > control	7	MNI
Coen et al. (2009)	12	26	Nonpainful and painful distentions to the esophagus during neutral and negative emotion	Painful esophageal distention > rest	11	TAL
Critchley et al. (2004)	17	/	Heartbeat detection task	Interoceptive attention > control	11	MNI

Denton et al. (1999a)	10	24 - 36 years	Genesis of moderate thirst by rapid i.v. infusion of hypertonic saline (0.51 M)	Corr. Na concentration/rCBF	14	TAL
Denton et al. (1999b)	10	24 - 36 years	Genesis of thirst by i.v. infusion of hypertonic saline (0.51 M)	Maximum thirst > rest	14	TAL
	10	24 - 36 years	Genesis of thirst by i.v. infusion of hypertonic saline (0.51 M)	Wet mouth > rest	9	TAL
	10	24 - 36 years	Genesis of thirst by i.v. infusion of hypertonic saline (0.51 M)	3 min satiation > rest	6	TAL
	10	24 - 36 years	Genesis of thirst by i.v. infusion of hypertonic saline (0.51 M)	14 min satiation > rest	10	TAL
Egan et al. (2003)	10	24 - 36 years	Genesis of thirst by i.v. infusion of hypertonic saline (0.51 M) and thirst questionnaire (0-10)	25 min post-Hypertonic > rest	16	TAL

	1	/	Genesis of thirst by i.v. infusion of hypertonic saline (0.51 M) and thirst questionnaire (0-10)	Maximum thirst > others	14	TAL
	1	/	Genesis of thirst by i.v. infusion of hypertonic saline (0.51 M) and thirst questionnaire (0-10)	Maximum thirst > others	22	TAL
	1	/	Genesis of thirst by i.v. infusion of hypertonic saline (0.51 M) and thirst questionnaire (0-10)	Maximum thirst > others	5	TAL
	1	/	Genesis of thirst by i.v. infusion of hypertonic saline (0.51 M) and thirst questionnaire (0-10)	Maximum thirst > others	9	TAL
Ernst et al. (2013)	18	27	Heartbeat counting task	Interoceptive attention > control	2	MNI

Evans et al. (2002)	6	25 - 32 years	Air hunger task	Air hunger > control	53	MNI
Farb et al. (2013)	16	42	Breathe monitoring task	Interoceptive attention > control	9	MNI
Farrell et al. (2006)	10	23.7	Thirst induced with i.v. infusion of hypertonic saline and pain provoked with pressure to the thumbnail. Ratings of pain, thirst and dry mouth	Pain > rest	11	TAL
	10	23.7	Thirst induced with i.v. infusion of hypertonic saline and pain provoked with pressure to the thumbnail. Ratings of pain, thirst and dry mouth	Maximum thirst > rest	18	TAL
	10	23.7	Thirst induced with i.v. infusion of hypertonic	Pain and thirst > rest	13	TAL

			saline and pain provoked with pressure to the thumbnail. Ratings of pain, thirst and dry mouth			
Haase et al. (2015)	7	21.86	Breathing load manipulation (anticipation, breathing load, post-breathing load) before and after Mindfullness training (mPEAK)	Loaded breathe anticipation, post-mPEAK > pre-mPEAK	3	TAL
	7	21.86	Breathing load manipulation (anticipation, breathing load, post-breathing load) before and after Mindfulness training (mPEAK)	Loaded breathe, post-mPEAK > pre-mPEAK	5	TAL
	7	21.86	Breathing load manipulation (anticipation, breathing load,	Post-loaded breathe, post-mPEAK > pre-mPEAK	4	TAL

			post-breathing load) before and after Mindfulness training (mPEAK)			
Haase et al. (2016)	46	28.93	Breathing load manipulation (anticipation, breathing load)	Loaded breathe > loaded breath anticipation	7	TAL
Haruki et al. (2021)	29	19–28 years	Heartbeat counting task	Heart attention > tone attention	8	MNI
Haruki et al. (2023)	35	21.61	Interoceptive attention task	Heart attention > visual attention	13	MNI
	35	21.61	Interoceptive attention task	gastic attention > visual attention	19	MNI
Hassanpour et al. (2018)	23	26	Modulation of cardiorespiratory function via injection of isoproterenol hydrochloride to cause tachycardia and dyspnea	Tachycardia and dyspnea, peak phase > rest	3	MNI
	23	26	Modulation of cardiorespiratory function via injection of	Tachycardia and dyspnea, recovery phase > rest	4	MNI

			isoproterenol hydrochloride to cause tachycardia and dyspnea			
Immordino-Yang et al. (2014)	47	18 - 30 years	Emotional experience task	Emotional experience > control (Chinese)	12	MNI
	47	18 - 30 years	Emotional experience task	Emotional experience > control (East-Asian American)	16	MNI
	47	18 - 30 years	Emotional experience task	Emotional experience > control (American)	16	MNI
Isaev et al. (2002)	6	39 – 44 years	Induction of linearised inspiratory resistance (24 cmH2O (l s_1)_1	Loaded breathe > rest	13	MNI
Kuehn et al. (2016)	12	/	Heartbeat and breathing monitoring task	Interoceptive attention > control	2	MNI
	12	/	Heartbeat and breathing monitoring task	FC, control > interoceptive attention	2	MNI
Liotti et al. (2001)	9	/	Inhalation of CO2 via face mask (FM) or mouthpiece	CO2 FM > CO2 MP	20	TAL

			(MP), questions rating breathlessness (0-100)			
	9	/	Inhalation of CO2 via face mask (FM) or mouthpiece (MP), questions rating breathlessness (0-100)	Corr. Breathlessness score/rCBF	14	TAL
May et al. (2014)	58	15–55 years	Soft touch	Soft touch, AD > YA = MA	12	TAL
	58	15–55 years	Soft touch	Soft touch, AD = MA > YA	7	TAL
	58	15–55 years	Soft touch	Soft touch, AD > MA > YA	1	TAL
	58	15–55 years	Soft touch	Soft touch, AD = YA > MA	1	TAL
	58	15–55 years	Soft touch	Soft touch, MA > AD = YA	2	TAL
Oberndorfer et al. (2013)	12	/	Visual anticipatory task viewing images of food and non-food neutral objects	Food anticipation > rest	4	TAL

Perini et al. (2015)	18	20 -32 years	Soft touch (5 different velocity, participants can choose repeated velocity or change) to arm and palm	Soft touch > rest	3	TAL
	18	20 -32 years	Soft touch (5 different velocity, participants can choose repeated velocity or change) to arm and palm	Soft touch, repeated velocity > change velocity	1	TAL
	18	20 -32 years	Soft touch (5 different velocity, participants can choose repeated velocity or change) to arm and palm	Soft touch, repeated velocity > rest (arm)	1	TAL
	18	20 -32 years	Soft touch (5 different velocity, participants can choose repeated velocity or	Soft touch, repeated velocity > rest (palm)	2	TAL

			change) to arm and palm			
Pollatos et al. (2007)	20	26.8	Heartbeat counting task	Interoceptive attention > control	10	TAL
	20	26.8	Heartbeat counting task	Corr. Interoceptive awareness/BOLD	4	TAL
	20	26.8	Heartbeat counting task	Interoceptive attention and physical exercise > control	7	TAL
Simmons et al. (2013)	14	29	Heartbeat and stomach monitoring task	Interoceptive attention > rest	13	TAL
Stern et al. (2017)	19	/	Heartbeat counting task and skin temperature monitoring task	Interoceptive attention > control	13	MNI
	19	/	Heartbeat counting task and skin temperature monitoring task	Interoceptive attention > control	8	MNI
	19	/	Heartbeat counting task and skin temperature monitoring task	Interoceptive attention > control	20	MNI

Terasawa et al. (2013)	18	22.9	Questions about emotional awareness, body awareness and personal possession in two temporal condition (now/usual)	Interoceptive attention > control	7	MNI
	18	22.9	Questions about emotional awareness, body awareness and personal possession in two temporal condition (now/usual)	Emotional attention > control	6	MNI
	18	22.9	Questions about emotional awareness, body awareness and personal possession in two temporal condition (now/usual)	Interoceptive attention > control	4	MNI
	18	22.9	Questions about emotional awareness, body awareness and	Emotional attention > control	17	MNI

			personal possession in two temporal condition (now/usual)			
Tracy et al. (2007)	17	30	Heartbeat counting task	Interoceptive attention > control	1	TAL
	17	30	Heartbeat counting task	Interoceptive attention > rest	2	TAL
	17	30	Heartbeat counting task	Interoceptive attention > control	1	TAL
	17	30	Heartbeat counting task	Interoceptive attention > control	1	TAL
	17	30	Heartbeat counting task	Interoceptive attention > control	2	TAL
Wang et al. (2007)	18	32	Dynamic gastric balloon distention	Gastric distention > gastric relaxation	13	TAL
Zaki et al., (2012)	16	19.1	Heartbeat monitoring task	Interoceptive attention > control	5	MNI